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Radar Detection of Hydrocarbon Gas Seepage Associated with Underground Oil and Gas Deposits

MERRILL I. SKOLNIK

Radar Division

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<p>Small, simple marine radars have been successfully used for finding gas seepage indicative of oil or gas producing fields. There has been some controversy about the method of operation and the physical phenomenon detected by the radar; but the basis for the technique is now better understood after discussions with the inventor, Robert Owen, and by observing how he operates in the field. It is believed that the radar is detecting the turbulence introduced in the lower atmosphere by the escape of hydrocarbon gases from the ground. Suggestions are offered for better understanding and exploiting this radar method for detection of hydrocarbon gases.</p>					
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RADAR DETECTION OF HYDROCARBON GAS SEEPAGE ASSOCIATED WITH UNDERGROUND OIL AND GAS DEPOSITS

SUMMARY

Simple marine radars have been used, with apparent success, by several petroleum-exploration companies for the detection of hydrocarbon gas seepage from underground deposits of oil or gas. The descriptions of the radar technique that have appeared in the patents and in publications are based on the radar signal being shifted in frequency on reradiation from the hydrocarbon gases--something analogous to a "microwave fluorescence." However, there is no theoretical or experimental evidence that a change in frequency occurs when microwave frequencies are reflected from a gaseous volume. This lack of theoretical and independent experimental support for the "fluorescence" model has caused many to be skeptical of the claims made by the users of such radars. Yet, the radar technique apparently has proven to be successful for its intended purpose.

In talking with Robert Owen, the inventor of this technique and one of its principal practitioners, it was concluded that the radar is not actually operated as described in the patents. Instead, it is operated as a more or less conventional radar with the receiver tuned to the same frequency as that transmitted. Robert Owen's success is attributed to his method of using the radar and in recognizing the distinctive spatial and temporal characteristics of the radar echoes as seen on a PPI display.

This report describes two trips made with Robert Owen to Decatur, Texas in June and September 1987 for the purpose of operating his radar and in exploring the nature of the phenomenon. Tape recordings of the PPI display were made and examples are included in the report. A new model is proposed for explaining what is seen by the radar. It is based on radar reflections from atmospheric turbulence induced in the lower atmosphere by the escaping gases.

The results reported here are based on very limited observations and very limited knowledge of the physics of gas seepage. There is much that has been learned about the radar detection of this phenomenon, but there is much more that needs to be determined. Suggestions are offered for (1) further measurements to provide more information about the phenomenon, (2) improvements in the radar equipment and in the operation of the radar, and (3) achieving a better understanding of the geophysics and atmospheric effects that are involved.

Even though the original explanation for this phenomenon is now known to be invalid, there is ample evidence that radar can be used for the detection of oil and gas deposits based on some characteristic of the gas seepage--which is postulated here to be turbulence induced in the atmosphere.

Acknowledgements

The writer's introduction to the use of radar for the detection of hydrocarbon gases was through the work sponsored by Dr. Frank Patten of DARPA which was undertaken by Dr. Richard Copeland of Energy Data Systems, Inc. Both of these individuals were helpful in my making contact with Robert Owen, which led to the efforts described in this report.

Robert Owen, of Hydrocarbon Gas Surveys, Inc., was most cooperative and helpful in my acquiring an understanding of the use of his radar for oil exploration. He also provided me with much background material about the phenomenon and its application. It was his radar that was used in the work reported here. These efforts were done on a "shoe string" and would not have been as successful if it were not for the participation of Robert Owen.

The experimental efforts conducted in September 1987 also could not have been accomplished without the engineering and experimental talents, as well as the enthusiasm, of both Don Hemenway and Pete Hansen of the NRL Radar Division. They worked in the hot sun of Texas under difficult conditions to provide the data that was obtained, and they were particularly helpful in trying to understand what was happening.

It is a pleasure to personally acknowledge that this report and any success of this effort is due to the expertise, support, and encouragement of the above mentioned three individuals: Robert Owen, Don Hemenway, and Pete Hansen.

1. BACKGROUND

Airborne imaging radar, such as Synthetic Aperture Radar (SAR) and Side-Looking Airborne Radar (SLAR), have been successfully employed for the exploration of oil.¹ Imaging radars are able to identify topographic features that indicate promising areas where oil might be found. The identification of these areas is followed by traditional exploration methods on the ground. Imaging radar is a proven technique that has been accepted as a means for finding oil.

There is another, quite different, radar method that has been used for finding oil or gas deposits. It is said to be based on detecting the hydrocarbon gases, associated with underground gas and oil deposits, that seep into the atmosphere. The technique is claimed to be successful and has been used by several commercial organizations; but there has been some uncertainty (and controversy) surrounding its validity, especially the physical mechanism on which it is supposed to be based. This radar technique is the subject of the present report.

This report is based on published information about the technique (of which there is very little), discussions with one of the inventors, and observations in the field with the inventor's radar. A major finding of this effort is that the radar is not operated according to the model described by the patents or in the publications. A physical mechanism is proposed that differs from that given in the patents for explaining how the radar might detect hydrocarbon gas seepage. This explanation is consistent with the radar observations and the little that seems to be known about the seepage of hydrocarbon gases from underground gas and oil deposits. However, there still is much to be learned about the phenomenon observed by radar.

There are two patents that claim underground gas and oil deposits can be found by the use of microwave radar based on the detection of hydrocarbon gases that seep upward into the atmosphere. One patent was issued to Robert Owen and Julian Busby in 1972², and the other to Gournay, et al. in 1979.³ In addition, the writer is aware of at least three others who have used this radar technique to locate oil and gas. The technique described in these two patents is quite distinctive. Both patents claim that when the radar transmits at one frequency (for example, 9375 MHz), the re-radiated echo signal from the gas seepage is at a different frequency (for example, 9361 MHz). That is, it is said that there will be a frequency translation on reflection from the hydrocarbon gases, apparently analogous to a "microwave fluorescence."

The problem with this explanation is that it is not likely that fluorescence (frequency translation of the echo) exists to any significant extent at microwave frequencies. As far as is known, there is no experimental or theoretical evidence for microwave fluorescence although there have been several unsuccessful attempts to show its existence. Its mention as the basis for a patent or in publications cannot be accepted as evidence without confirmation. (The only verified example of a frequency translation on reflection is when a target has metallic parts in contact that form natural nonlinear diodes, as in the techniques known as RADAM and METTRA⁴, but these are not likely to be found in scattering from gases.)

Thus the mechanism described in the patents has to be suspect. However, there have been too many examples of the successful use of this radar technique to dismiss it simply because there is no evidence for the model on which it is supposed to be based. In such a situation, it is important to examine carefully how the radar is actually being used. The results obtained with radar should not be thrown out just because the theory on which it is supposed to be based cannot be verified. (Unfortunately, this is done all too often.) Discussions with representatives of oil companies and others familiar with the patents seem to indicate that this radar method has not been widely accepted because the theoretical model cannot be verified. Thus it is important to determine what is actually happening with the radar before dismissing the technique.

The success claimed for this radar technique by its proponents is impressive. The brochure⁵ of Hydrocarbon Gas Surveys of Dallas, Texas claims that on the basis of 25 wildcat sites evaluated by radar which indicated the potential for oil or gas, 19 drilled wells resulted in the discovery of new gas or oil. This is a success rate of 75 percent, as compared to an 18 percent success rate for exploration drilling in the United States in 1981. Hydrocarbon Gas Surveys also claims that of 23 wildcat drillsites where no hydrocarbon gas was indicated by radar, all 23 resulted in non-commercial wells or dry holes when the well was drilled in spite of the negative prediction. If these claims are correct, then it is likely that the operators of radar for hydrocarbon gas detection have found a way to use radar successfully in spite of the unlikely description based on microwave fluorescence that is offered in the patents.

The writer became interested in this radar technique mainly because of the claim that there was a frequency translation on reflection from hydrocarbon gases. He was aware of a similar explanation for an entirely different atmospheric phenomenon in which there was thought to be a frequency translation of the radar signal on reflection from a particular type of target, but which upon close scrutiny could be readily explained by a more easily accepted scattering model. It turned out that the explanation that was successfully applied in this other example, did not apply for the case of hydrocarbon gas detection. However, this effort led to a plausible hypothesis for explaining what might be happening in the use of radar for oil exploration.

In order to obtain a better understanding of what actually takes place in using the radar, the writer arranged to meet on February 27, 1987 with Robert Owen, President of Hydrocarbon Gas Surveys, one of the inventors and practitioners of this radar method for finding hydrocarbon gas seepage. The meeting with Robert Owen was quite informative and cleared up many of the problems associated with the patents and in understanding how the radar is actually used. The major consequence of this meeting was that it was agreed that the radar receives at the same frequency as that transmitted. There is no frequency offset. There is no microwave fluorescence. The radar is operated in a more or less conventional manner; however, the target is different from normal radar clutter targets. The key seems to be in how the radar is operated and how the desired target is recognized. (What was learned at this meeting is described more fully in Appendix A.)

In addition to the visit with Robert Owen in February, the writer accompanied him for two days in June to witness how he actually used his radar and to observe the phenomenon. Three days in September 1987 were also spent in the field with Owen's radar. In both June and September, the majority of the radar observations were made at a natural gas field one mile east of Decatur, Texas. These were old fields nearing the end of their useful production so that the effect might have been weaker than expected of a new field. Nevertheless, definite and distinctive effects were seen that are assumed to be due to seeping hydrocarbon gases.

2. DESCRIPTION OF THE RADAR AND METHOD OF OPERATION

The radars used for the detection of hydrocarbon gases have been relatively simple and of low power. An example is the Raytheon Type 2700 Marine Radar commonly found on ships and boats. The model used by Hydrocarbon Gas Surveys operated at X-band (nominally 9410 MHz), with a peak power of 5 kW, an antenna beamwidth of 3°, and an antenna rotation rate of 23 rpm (2.61 seconds revisit time). When operated at a 1500 Hz pulse repetition frequency and a 0.08 μ s pulse width, its average power was about 0.6 watt. This is a relatively low average power for such a radar; but it is operated at a very close range, sometimes as short as one or two thousand feet.

The Raytheon Type 2700 X-band Marine Radar was mounted on top of a van, as shown in Fig 1 taken during the September 1987 tests. Robert Owen said he often operates with a maximum display range of 2 nmi, with 1/2 nmi (3000 ft) range rings. The writer usually preferred the shortest display range of 1/2 nmi and range rings of 1/4 nmi (1500 ft), especially when the van was stopped. The pulse width on both the 2 nmi and 1/2 nmi displays was 0.08 μ s (80 ns), which corresponds to a range resolution of about 12 m, or 40 ft. (The Raytheon brochure, however, gives the resolution as 65 ft.) At a range of 1500 ft, the 3° antenna beamwidth provides a cross-range resolution of about 24 m, or 80 ft. The STC (sensitivity time control) was not used so that weak echoes at short range would not be attenuated in the receiver. Appendix B provides an approximate estimate of the range capability of the Type 2700 radar. It indicates this radar might be capable of detecting a target with a radar cross section of 0.025 m² at a range of 1000 m; and a target with a cross section of 0.0002 m² at a range of 300 m, or 1000 ft. If it seems strange that such a small radar can see such a small target, keep in mind that the range is short and that the fourth power relation between range and radar cross section of the target is a very powerful factor at short ranges. (Similar radars, with a slightly larger antenna, have been used by entomologists to observe individual insects at short range. A "typical" insect might be about 0.00001 m², and a "typical" small bird might have a radar cross section of perhaps 0.001 m².) In actual operation, the gain of the radar receiver was set to a lower (unknown) value than the maximum so that the radar cross section that was detected was probably higher than the above calculations based on full receiver sensitivity.

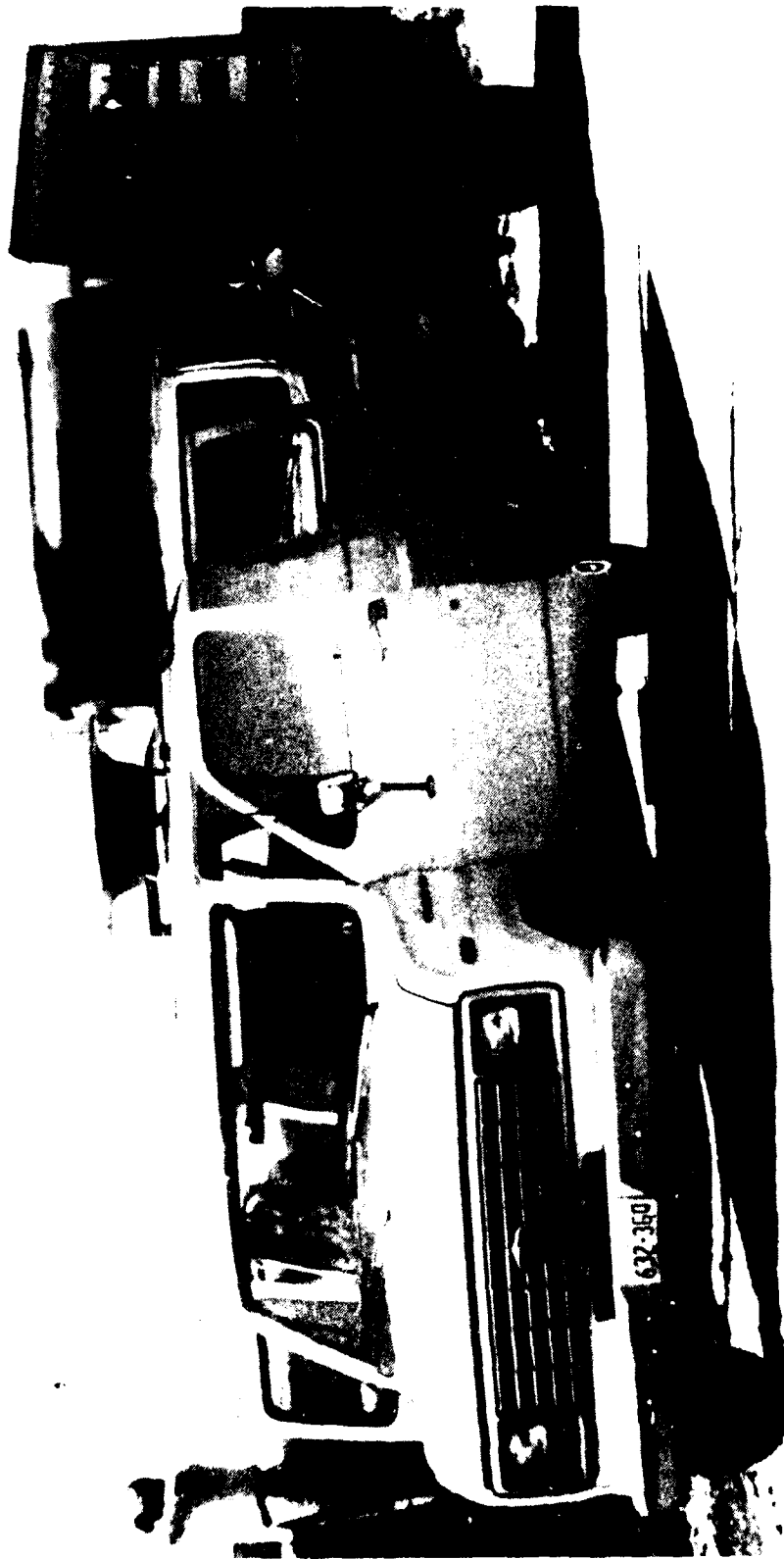


Fig 1 - Hydrocarbon Gas Surveys, Inc. van with Raytheon Type 2700 X-band radar antenna mounted on top. The rental truck behind the radar van contained NRL equipment.

3. OBSERVATIONS DURING JUNE 23 AND 24, 1987

The writer accompanied Robert Owen in his radar van on June 23 and 24 to observe what he saw and how he operated. It was exploratory in nature and had the purpose of determining whether a more careful investigation should be made to document the effect. The area observed was to the northwest of Dallas, Texas (just east of Decatur, Texas). The terrain might be described as gently rolling. The weather was hot and there was sun with cumulus clouds. As he drives along, Owen looks for a relatively clear field without trees, brush or other vegetation since these can produce a clutter echo that masks the desired echo. He does not like plowed fields. They appear dark (no echo on the PPI) and do not show the characteristic echoes expected from hydrocarbon gases. (Owen said that the phenomenon can be detected again after crops grow on the plowed fields to a height of several inches.) If a relatively open field produces echoes (extending out just beyond the perpendicular markers, or "wings," on the radar display cursor--which might be about 1/2 inch, and correspond to 400 to 500 ft), the van is stopped and the region searched with the scanning radar. Owen says he looks for a "black hole" and a change of shape of the hole with time. In the examples shown me by Owen, the black hole is usually near the edge of the clutter. I noted that instead of thinking of it as a black hole, it could be considered as several scatterers clustered in a group. The grouping of the individual scatterers can result in what appears as a black hole (absence of other clutter). The individual echoes seemed to fluctuate from scan to scan (2.6 s). This made the "center" of the cluster (Owen's "black hole") also fluctuate. The size of the individual echoes of the cluster seemed to be slightly larger than the radar resolution. (It was determined later from scope photography during the September tests that the echoes were not always greater than the resolution.)

Owen adjusts the gain so that the display has a black background (in the absence of echoes). This is different from normal radar procedure, since most PPI displays are operated so that there is a trace of background noise visible. This usually provides the best detectability. Owen might be using a lower gain so as to avoid swamping the desired effect because of the limited dynamic range of the display. The gain control on the radar had numerical settings from 1 to 10. The maximum gain was at 10. Owen liked to operate with a gain setting of about 3 or 4 (I usually used 4). When a suspected target echo was obtained, he reduced the gain (e.g.; to 2), and the hydrocarbon gas echo would disappear; but usually the nearby clutter would not. This indicates that the target echo was weaker than the surrounding clutter.

It was found that a gain setting of 8 was necessary to produce a slight background noise level on the PPI display. Thus the radar sensitivity in Owen's operation (gain setting of 3 or 4) was probably much less than it could be. (It should be cautioned that the numerical values of the gain-control knob should not be used to indicate quantitative levels of the echoes since it is not likely that the gain control is linear.) I did not get an opportunity to examine whether the level 8 setting, with its greater sensitivity, saw the desired target echoes. A higher gain might allow detection of this effect at a greater range than normally used when the gain is adjusted to provide a black background to the scope display.

The usual method of operation had Robert Owen driving and me sitting at the radar scope in the back of the van. Most of the time I was on my own, so I usually observed the echo a little differently than he normally did. I tended to detect echoes that were in the clear, outside of the clutter region. Owen preferred to detect the effect near the edge of the clutter (at least during the time we were operating). I often asked him to leave the front of the van and look at the scope to ensure that I had detected the same type of effect he did.

Several different fields were observed, some more than once and some on both days. All were either gas fields or fields with no producing wells evident. The most interesting was the first producing field he showed me. The field had a number of gas wells. (My guess is that the wells were about 1/4 to 1/2 mile apart, but this is from memory and nothing recorded at the site.) Owen looked at the record attached to the well and concluded they were old and were not large producers. There were some houses in the vicinity which showed up well on the display. In this field I observed three different areas where the scope showed the characteristic cluster of echoes that Owen says is indicative of gas seeps. The cluster was characterized by having three to perhaps six individual echoes which seemed to vary slightly in size and position from scan to scan, but which remained in the same general location. In one case, the cluster extended over an azimuth angle of 20° at a range of 1500 ft. This corresponds to a cross-range dimension of about 500 ft. On other occasions the cluster consisted of several blobs within a distance of 300 to 500 ft. Two of these clusters were about 500 ft or so from the gas well. (The well had a small tank surrounded by a wire fence.) There were no obvious reflectors from the area that produced radar echoes, except for uncut grass. (In one case there was a solid echo about 500 ft from the cluster. Nothing was seen visually from the radar van; however, once at the site of the echo it proved to be from a steel rod placed in the ground. The rod extended about 3 ft and might have been 1/2 inch in diameter. All dimensions are from memory, nothing was measured and recorded in the field, except for dimensions obtained from the scope.)

The "apparent" direction of the movement of the echoes was observed in one case and was found not to be in the direction of the wind. (The wind direction could be readily obtained from a flag flying from a nearby house.) However, based on later recordings of the scope (during the September tests) it is not believed there is significant echo movement. Furthermore, when a cursor was placed over the cluster, no long-term drift of the cluster was indicated. (The observations of movement were apparently illusionary, as discussed later.)

The echoes from one cluster changed with time from an individual blob to a pair of smaller blobs. It is almost as if the echo was a vortex pair that was sometimes resolved into two echoes and sometimes unresolved as one larger echo.

In the fields that Owen said were non-producing (gas wells were absent), the individual radar echoes remained the same from scan to scan. In one such field, however, there was an area exhibiting a weak radar echo similar to that observed over the producing fields with gas wells. Owen did not believe

that this was necessarily a false alarm, but it might have been an indication that gas was present since the field was not too far from the producing fields.

With the wide elevation beamwidth it could not be determined if the radar echoes were from hydrocarbon gases at the surface or above the surface. However, it did not appear as if the echoes were predominately from the surface, since ground clutter was not seen superimposed on the target echoes. The elevation coverage of the 20° beamwidth corresponds to about 500 ft at 1500 ft, the approximate range at which several echoes were observed. In principle, therefore, the gaseous targets seen by the radar could extend to several hundred feet. On one occasion when an echo was found, the van was moved so as to be partially masked by intervening terrain. Targets were not observed, indicating they might be close to the surface; but this was not a good indication since the masking in this particular case might have been too severe. (The extent of the echo in elevation is important to determine if the mechanism producing the echoes is to be understood and if the use of the radar is to be optimized.)

4. OBSERVATIONS DURING SEPTEMBER 15-17, 1987

The purpose of this trip was to further examine the nature of the echoes from the Hydrocarbon Gas Surveys radar operated by Robert Owen, to attempt to record on video tape the radar PPI display for later examination, and to employ a pencil-beam antenna that was trainable in elevation so as to determine the vertical structure of the phenomenon. In addition to Robert Owen and the writer, Donald Hemenway and J.P. (Pete) Hansen from NRL were major participants in this exercise. Hubert McQueen, from Hydrocarbon Gas Surveys, also assisted during these three days.

The testing was planned to be conducted at an old oil field just to the east of Hamlin, Texas, about 40 miles northwest of Abilene. There were several working oil wells throughout the field, and the radar was set up in the vicinity of one of them. The field contained cotton. The appearance of the field on the radar display was deceiving at first since it looked as though the radar was imaging the individual rows of cotton. When it was realized that the resolution of the radar did not permit this, we were informed by someone familiar with growing cotton, that the earth was contoured and terraced to allow drainage and prevent erosion. Visual examination of the field confirmed that it was the underlying contour of the earth we were probably seeing rather than the individual rows of cotton.

The radar did see echoes that were thought to be similar to those expected from hydrocarbon gases. However, it was not as convincing as the observations made in June. There was a strong wind blowing, so there was concern that what was seen by the radar might be due to the cotton moving in the wind rather than the escaping hydrocarbon gases. We had no way to be sure at the time that this was not happening. Another possible factor in poor results was that the radar might actually be receiving echoes from the gas, but the strong wind might be dispersing the gas and make the echoes more diffuse and difficult to recognize. (Reference 6 indicates that strong winds make observation of this effect difficult.) It had rained heavily the night before so that the ground was muddy and there were

puddles of water on the ground. These puddles might have inhibited the release of gas. Whatever the cause, it was obvious that the radar was not observing good echoes. Robert Owen said he visited the same site several weeks earlier and had much better results. Because of the limited time available to us for these tests, it was decided not to chance a similar experience the next day. Therefore, it was thought best for the remaining two days to return to the same gas fields near Decatur that were visited in June. Unfortunately, there were no recordings made of the PPI display at the field near Abilene.

It should be mentioned that on the trip back to the motel at the end of the day, a similar cotton field many miles away from the oil field was observed with the radar. Presumably, this similar field was not over oil or gas. The radar image was quite different from that seen at the oil field. The echoes on the display were stable from scan to scan and there were no echoes that fluctuated as was the case at the oil field. This difference gave confidence that we might have actually been observing hydrocarbon gas at the original cotton field rather than the cotton moving in the wind.

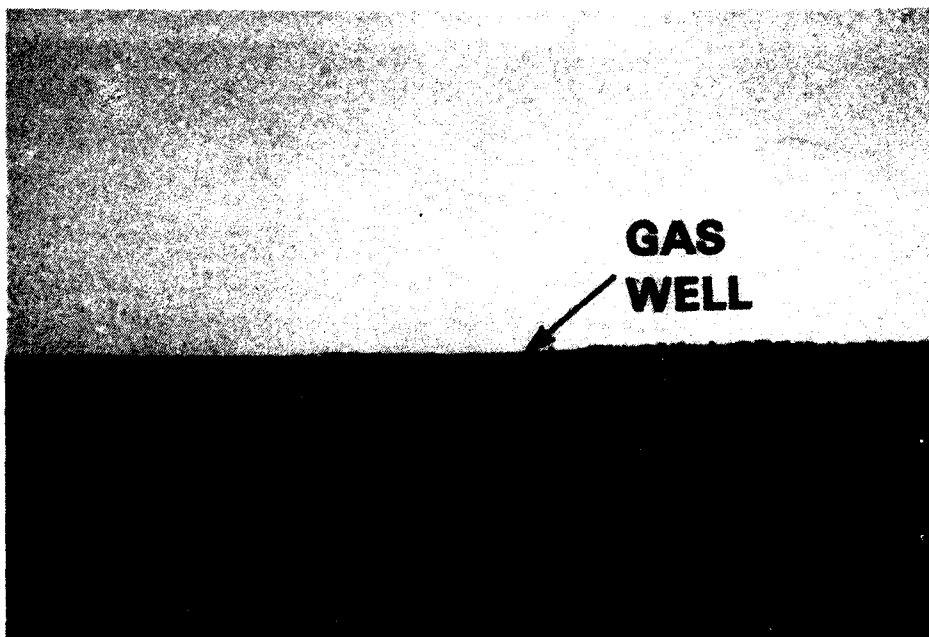
On the 16th of September the radar was set up along a dirt road about one mile east of Decatur in the midst of a gas field. The field was one of those that was observed during June. Similar effects were seen on the radar screen as were seen in June. A Sony video camera recorded the radar display so that it could be reviewed at leisure back at NRL. Unfortunately, the PPI of the small marine radar was not as suitable as might be desired for recording. The display was not bright and normally had to be viewed with a hood to exclude ambient light. The hood used for visual viewing could not be used with the Sony camera, but an adequate substitute was made by Kate Hansen. There was also difficulty in keeping the video in one place on the screen. A Sony camera is not the same as a wideband tape recorder that records directly the radar video signal, so that much is lost when viewing on a TV monitor. Nevertheless, scan-by-scan analysis of the Sony tape provided some interesting information that was not appreciated when viewing the radar display in real time.

The radar van was stopped on the side of a dirt road (Fig 2a). There were three gas tanks visible. One is barely visible in Fig 2b. Figure 3 is a map of the area showing the approximate location of the radar. Range circles of 1500 ft and 3000 ft are drawn. Although the map was the latest available from the U.S. Geological Survey, it was obviously quite out of date. A road about 100 ft to the west of the radar, leading to highway 380, was not indicated; at least one of the gas wells (1039 on the map) was moved; and the small lake (or large pond) seen so well on the radar was not in evidence on the map. The locations of two large radar echoes that were almost always seen by the radar are indicated in Figure 3. The larger echo is from a gas tank and the smaller is also thought to be some man-made object rather than a natural echo.

The NE quadrant of the display exhibited many more clutter echoes than did the SE quadrant, probably due to the upward slope of the land. The contours in Figure 3 indicate the radar generally looks uphill in the NE quadrant but somewhat downhill in the SE quadrant. This is consistent with the statement of Robert Owen that when flying the radar in a helicopter it



(a)



(b)

Fig 2 - (a) View looking east from radar located about one mile east of Decatur.
 (b) View looking southeast from radar showing gas tank (at center) and possible radar echo from tree at right hand side of picture.

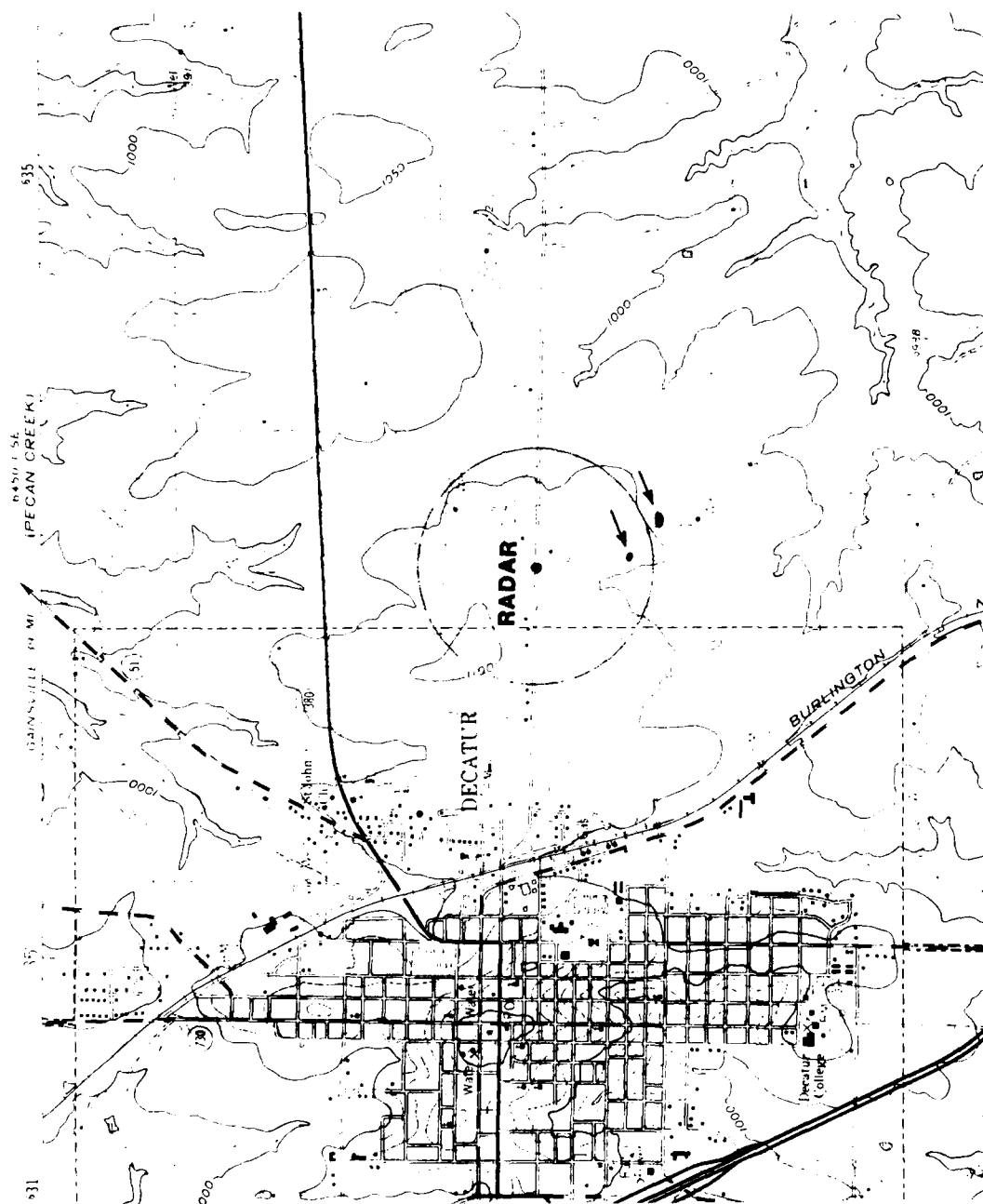


Fig 3 - Map of area showing location of radar. The range circle is 1,500 ft. Location of two echoes are indicated (Nos. 1 and 2 in Fig 4) that were always seen by the radar.

is better to fly downhill rather than uphill. (The likely reason is that less clutter is seen looking downhill and the gases which are located above the surface can be more readily detected without the masking of the larger clutter echoes.) No echoes of any consequence were seen in the SW sector. Gas wells were not evident in this region. Ground clutter was observed in the NW sector (the ground also rose in that direction), but little attention was given to that sector. Echoes like those we were looking for were seen in both the NE and SE sectors. These will be called echoes from hydrocarbon gas seepage in this report since they are the type of echoes so identified by Robert Owen. It is likely they could be from hydrocarbon gases, but this needs to be verified in the future.

Notes taken at the time indicated a likely hydrocarbon gas echo from an area just north of the tank that was located in the NE sector (at an azimuth of 20° east of north and a range of 1400 ft). The loss in dynamic range in recording on the Sony did not make analysis of this region easy. Therefore, the analyses of the tapes concentrated on the SE sector where there were fewer clutter echoes to compete with observation of the echoes thought to be from gases.

Figure 4 is an approximate sketch of the various echoes seen in the SE sector on the radar display when the gain is relatively high. (The setting was at number 5 or greater on the gain control.) The radius of the circle centered at the location of the radar represents a range of 1500 ft. The numbers in this figure identify the following:

No. 1. This was believed to be a large tank that was visible from the radar site and can be barely seen in the center of the photo of Figure 2b. This echo was always present, even at the lowest gain setting. It was a large, steady echo and did not fluctuate. The map shows a gas well in the vicinity, but not at the location indicated by the radar; so it is assumed the well might have been moved since the map was made. Note that the size of the echo is much greater than the resolution cell size of the radar. (Recall that the antenna beamwidth was 3° .) This might be due to the fact that the tank is enclosed by a chain link fence so that the echoing area is larger than the tank itself. Also, the echo is strong, which could cause the trace on the display to be larger than the actual physical size of the target.

No. 2. This appeared to be from a hard target, but we did not enter the site to correlate it with some actual object. (In hindsight, it is important to identify the origins of all the echoes seen by the radar. This was not appreciated at the time of observation, but it is something that should be done in any future field observation.) Echo No. 2 was almost always present, except at the lowest gain settings.

No. 3. This was present a large part of the time, but was much weaker than echoes Nos. 1 and 2. Its origin is not known, but it might be due to a tree that is visible in Figure 2b. The tree in the figure is at the same approximate azimuth as this echo.

No. 4. This appeared to be a man-made object rather than a tree.

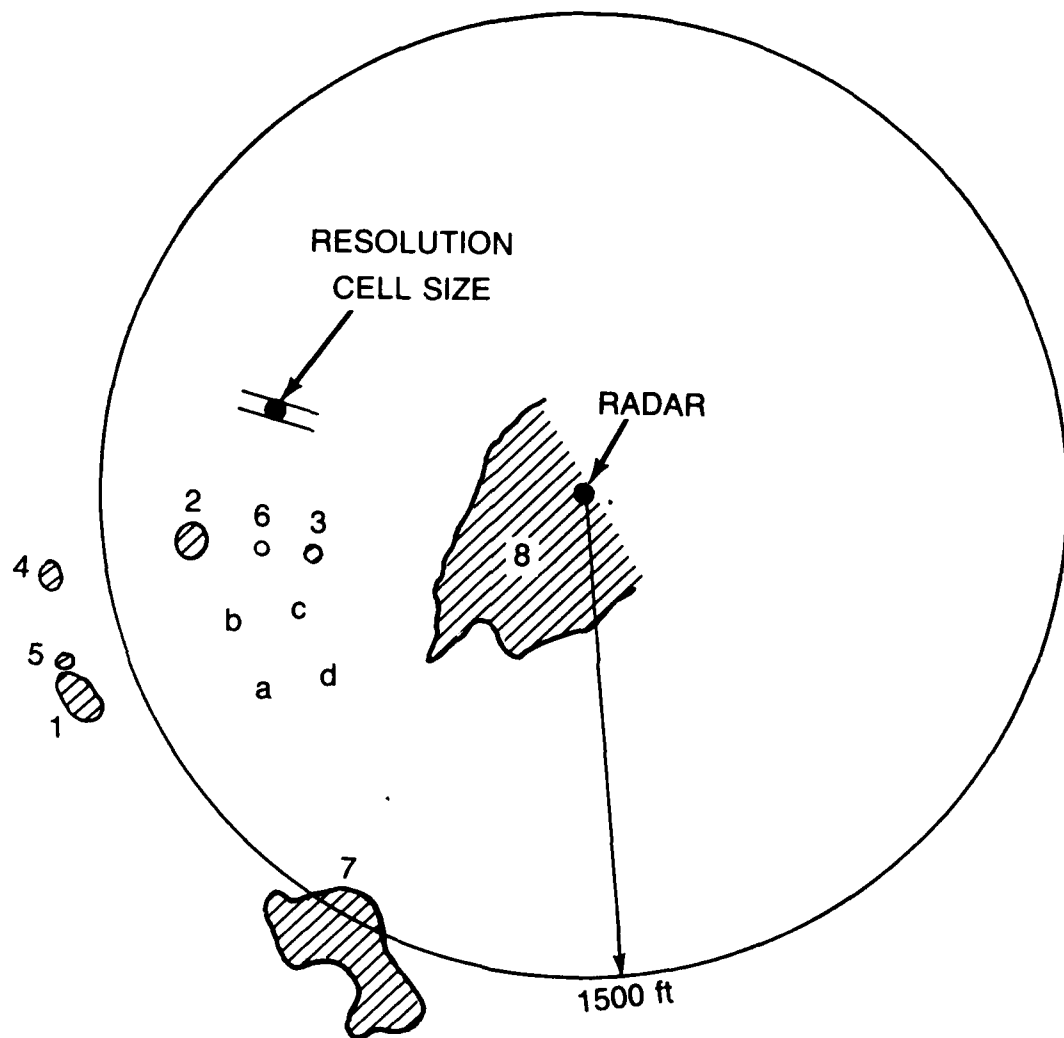


Fig 4 - Approximate sketch of the SE sector of the radar display as observed from viewing the Sony tapes, showing the various echoes of interest. These echoes are identified in the text.

No. 5. At the higher gain settings this small echo appeared. It might be due to whatever corresponds to the white spot just to the right of the tank in Figure 2a. (It is difficult to see these visually small objects on the photo, and even more difficult on a reproduction.)

No. 6. This was a small echo seen only with a high gain setting.

No. 7. Trees were noted in the vicinity of this area from examination of the photos taken from the radar site. However, the trees seen in the photo extend over a wider azimuth angle than the radar echo. This might be due to the trees being at different ranges, something difficult to discern from a photograph. Again, this illustrates the importance of identifying in the field every major object that appears on the radar display. This is necessary to ensure that what is thought to be echoes from gases are not due to other scattering objects.

No. 8. This is the near-in ground echo. Its extent varied with the receiver gain setting.

All of the above are believed to be due to reflections from man-made objects or large trees. (Small brush did not seem to produce significant echoes.) The approximate size of the radar resolution cell (estimated to be 3° in azimuth by 40 ft in range) is shown in Figure 4 for comparison. The echoes in this figure, whose approximate locations are indicated by the letters a to d, were different from the others and are thought to be reflections from hydrocarbon cases. They consist of a number of individual, relatively weak scatterers occupying an area of about 300 to 500 ft in dimension. Within this region there were at least four separate scattering regions. Nothing obvious was seen visually from this general area, other than tall grass. The topographic map shows a dirt road passing through the area, but this was not evident from the radar site. The distance from the gas tank (echo No. 1) to these echoes varies from about 500 ft to about 800 ft. Not all the echoes in regions a to d were seen on each scan or with lower gain settings.

Scope Photography. Figure 5 shows a sequence of photos taken of the Sony tape as seen on the TV monitor. The reproduction of photography of a TV monitor showing a weak radar display results in considerable degradation of the image originally seen on the radar display in the field or even what is seen on the TV monitor. An apology is offered if the reader is unable to discern from the figures what is described in the text.) The tape was in "hold" so that a still picture could be photographed. The brightness of the display varies with angle, it being brightest at the position of the rotating strobe line and decreases in intensity in the counter-clockwise direction. The brightness of the echoes in these pictures depends on how far away they are from the strobe line. The position of the strobe line could not be controlled as well as might be liked because of the appearance of horizontal interference lines seen in some of the pictures. The brightness of the display can also vary if the tuning of the radar drifts with time, which is not unlikely. A rough "calibration" of the echoes from hydrocarbon gases can be had by noting the brightness of echoes Nos. 1 and 2. The strength of these two echoes usually remained fairly constant.



(a)



(b)



(c)

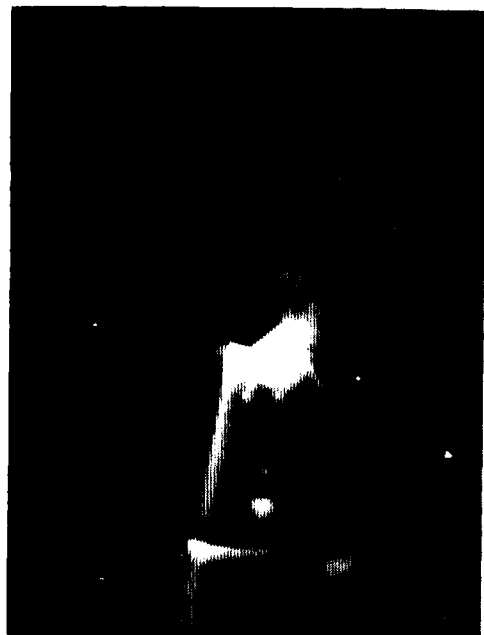


(d)

Fig. 5 — Sequence of photos of the Sony TV monitor. North is at 90° . Area of interest is between 8 and 9 o'clock (indicated by arrow in [a]). Range circle is 1,500 ft. Gain setting of 3 in (a); all others are gain setting 5. Echoes of interest are seen with gain setting 5, but not with 3. Time interval between frames (a), (b), (c) and (d) is one scan of the antenna (2.6 s). Frame (e) is 3 scans after (d), (f) is one scan after (e), (g) is 2 scans after (f), and (h) is 2 scans after (g). Total time frame (a) to (h) is about 18 seconds. The broad horizontal stripe in some frames is a recording artifact. The black "area" in the center of each frame is the location of the antenna beam at the time the photo was made. The strobe line at about 9:30 in each frame is the location of the antenna beam at the time the photo was made.



(e)



(f)



(g)



(h)

Fig. 5 — (Continued) Sequence of photos of the Sony TV monitor. North is at 90° . Area of interest is between 8 and 9 o'clock (indicated by arrow in [a]). Range circle is 1,500 ft. Gain setting of 3 in (a); all others are gain setting 5. Echoes of interest are seen with gain setting 5, but not with 3. Time interval between frames (a), (b), (c) and (d) is one scan of the antenna (2.6 s). Frame (e) is 3 scans after (d), (f) is one scan after (e), (g) is 2 scans after (f), and (h) is 3 scans after (g). Total time from (a) to (h) is about 18 seconds. The broad horizontal stripe in some frames is a recording artifact. The black "area" in the center of each frame is a mask to reduce blooming of the display. The strobe line at about 9:30 in each frame is the location of the antenna beam at the time the photo was made.

Eight consecutive scans, 2.6 seconds apart, are shown in Figures 5a to h. (The SE quadrant, which was the region of interest, is in the lower left side of each photo. That is; north is to the right, at about 90°.) In Figure 5a the gain setting is at 3. Only the strong targets (echoes Nos. 1, 2 and 3 in Figure 4) are seen. The trees (No. 7) at the bottom of the display can also be discerned. The gaseous echoes in 5b to 5h appear to change from scan to scan. When first observing the echoes on the radar display in real time it was thought they moved with the wind. Closer examination showed this was not correct. Careful observations of the echoes show they will fluctuate (and change in size) with time, and might not appear on each scan, but they tend to remain in about the same place (more or less). A change in size of the radar "blobs" seen on a display can be due to a change in physical extent or to a change in radar echo signal strength. Either might be occurring here. It is not unusual for radar echoes from atmospheric gases to change both in physical size and echo strength with time. If the echo signal strength changes were due to constructive and destructive interference among multiple scatterers within the radar resolution cell, as is usually the case with normal clutter echoes, the physical extent of the echo might not change much but the amplitude will fluctuate. Fluctuations due to interference of multiple scatterers can be much more rapid than the scan rate of the antenna. Examination of the spectrum of the amplitude fluctuations of echoes suspected of being from hydrocarbon gases should provide an important clue to aid in verifying the source of the echoes. This is something that should be done in future tests. Currently, it appears that the echoes from the suspected areas of hydrocarbon gases fluctuate at a rate different from that of natural clutter.

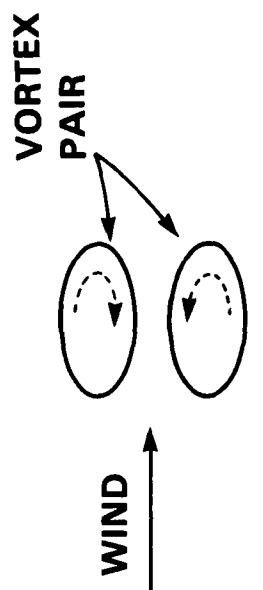
Echoes from suspected hydrocarbon gas were found not to be distributed over the entire area, but consist of a number of small cells, each of which is not large compared to the resolution cell size (theoretically, about 40 ft by 40 ft at a range of 1000 ft.) Thus these individual echoes might be from an area comparable to the radar resolution cell size, or less. However, individual echoes from this region have also been observed to be of greater size than the resolution cell size.

When observing the display in real time, one might characterize these echoes as "moving about" from scan to scan. However, as mentioned, they do not actually move significantly from scan to scan. Their fluctuation characteristics make them appear to move from scan to scan (like a stroboscopic effect), but the echoes apparently do not change their locations significantly. They mainly change their amplitude, which means they might not appear on every scan. The result is something that might seem like an apparent motion. A few echoes, however, have been noted to change slightly in location over a period of time, but the significance is not fully understood at present. This might be evidenced by gases moving in the wind. (It might be noted that even "hard targets, such as the suspected tree of No. 3 are not always seen on every scan.) Our observations of this phenomenon are consistent with those of others, as evidenced in this quote taken from reference 6: "The phenomenon manifested itself as a "shimmering" effect on a PPI (Plan Position Indicator) radar scope where targets appear, disappear, and change shape even though no visual hard targets exist in the vicinity."

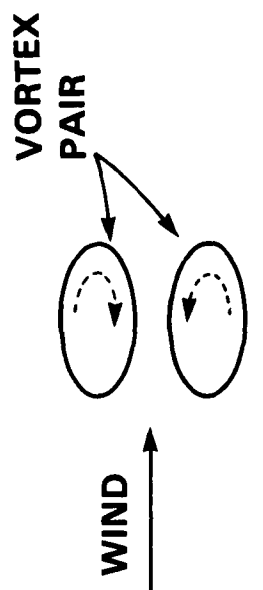
It might be asked whether escaping hydrocarbon gas would appear as the several discrete echoes seen in Fig 5 or whether it should appear as a continuous "cloud" over this area. The author is not aware of how gas seepage is distributed over an area; that is, whether it diffuses out uniformly over an area, whether it seeps from fracture lines, or whether it is concentrated in a few distinct spots. It is known, however, that natural convective (thermal) cells begin near the ground as a series of small individual cells even though the surface may be uniformly illuminated by the sun. As they rise, the cells join together to form larger, but fewer, cells. Therefore, from the little that is known at present about this phenomenon, it is not obvious that the echoes from gas seepage should be expected to appear as from a large distributed scattering region or from a number of individual patches. (It is interesting to note that the nature of the gas seepage depicted in the 1939 patent of Blau, to be mentioned later and shown in Appendix C, is consistent with the radar observations described here.)

During the June observations at the same gas field as in the September tests, but a different echoing region, it was noted that some of the individual echoes resembled what might be expected from a vortex pair. Convection can appear as two closely spaced equal circular regions rotating in opposite directions. This is a vortex pair. It has a distinctive appearance. It was noted that at times an individual echo from the suspected region of hydrocarbon gas would appear as a single blob and at times as two smaller blobs occupying the same area. On one occasion it was seen that each of two nearby blobs (separated about a few hundred feet) would change back and fourth from a single blob to two smaller blobs, reminiscent of a vortex pair, on every scan. Of major interest was that the orientation of the vortex pair was what would be expected from the observed direction of the wind. Figure 6a shows how a vortex pair might be generated by the wind. This is a drawing of a horizontal cut through the plume. The arrows show how circulation within the plume is developed. Figure 6b depicts the formed vortex pair. The formation of the vortex pair in this manner requires a wind. The ability of a radar to discern the two components of the vortex pair depends on the resolution capability of the radar. With low resolution or a small plume, the vortex pair would appear as a single blob to the radar. The same would be true if the wind were light. This information about the generation of a vortex pair was provided the writer by Professor Jin Wu of the University of Delaware, who has reported on studies of the generation of turbulent vortex pairs under laboratory conditions.⁷ It would seem that if the wind were very strong the gases would be dispersed and there might be no well-defined vortex pair or even a recognizable plume.

What appeared to be an echo from a vortex pair was also seen during the September observations. Two examples are shown in Fig 7. The echo from the region b (location indicated in Fig 4) is shown as a pair in these two photos. At other times there was only a single echo. The orientation of the pair is consistent with the approximate direction of the wind, which was estimated to be from about SW at 8-10 km. (As mentioned previously, the resolution in these photos is far worse than the radar display.) The echo from region a in Fig 7a also appears as two, but they are relatively far apart and could be echoes from separate features. (It

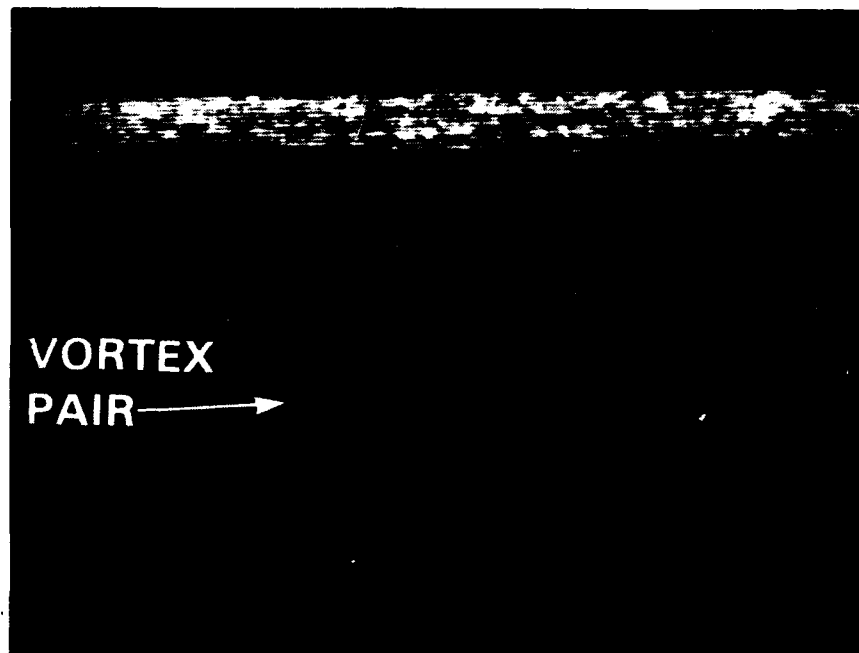


(a)



(b)

Fig 6 - Development by the wind of a vortex pair (b) from a plume (a).



(a)



(b)

Fig 7 - (a) A vortex pair at location area b, indicated in Fig 4.
 (b) A single blob from the same location. Time between frames is almost 8 s (3 scans).

is also possible that the echo from region b is from two distinct sources rather than a vortex pair; the conjecture that a vortex pair is sometimes seen should be proven in future observations.)

One or a few observations, of course, do not make a theory. However, it is encouraging that the nature of the echoes seen in the photos in regions a to d (Figure 4) is not inconsistent with what might be expected from gases in the atmosphere.

It should be cautioned that what is reported here is based primarily on limited observations of one gas field in Decatur, Texas. It should be expected that the details of observations made at other locations might be different because of differences in atmospheric conditions, as well as in differences in the nature of the gas seepage.

Echoes From the Pond. When the gain control was turned up to its maximum setting of 10, the radar display was filled with clutter echoes. However, the pond in the NE quadrant was dark; that is, there were no echoes visible from the surface of the water. Since the surface of the pond was calm and flat, this was to be expected. On some scans, however, one or two distinct echoes were noted from the pond. They would be seen on only one scan or at times they would be at different locations on successive scans. These echoes were puzzling, but the writer walked down to the pond and noticed that on occasion a flock of five birds flew across the pond low over the water. Thus it is likely that the echoes over the pond were from birds. The next day, it was found on one occasion that an echo existed at the same location near the center of the pond for several scans. If this was due to a bird, it might be one that sat on the water during that time.

The birds that were observed were not identified, but they were small. If the cross section of an individual bird is guessed to be about 0.001 sq m, the five birds would have a cross section of about 0.005 sq m. They were seen only when the gain of the display was set high. Since the gas echoes were seen on lower settings (level 4 or 5) it is concluded that the radar cross section of the gas was greater than that of the birds. It is guessed, therefore, (based on admittedly weak evidence) that the radar cross section of the gaseous echoes might be between 0.01 and 0.1 sq m.

5. COMMENTS ON THE CLAIMS FOR THE EXISTENCE OF A FREQUENCY TRANSLATION

The phenomenon of a frequency translation on reflection from hydrocarbon gases has already been mentioned previously in this report as being unlikely in spite of it being the basis for two patents (refs 2 and 3) as well as being mentioned in published papers and reports. A recent example is a paper⁸ in the Oil and Gas Journal which describes the use of radar for detection of hydrocarbon gases and explains the phenomenon on the basis of a frequency translation. A large part of this short paper is devoted to discussion of the frequency translation. The paper states: "the receiver is not tuned to the transmitter frequency. Instead, it is sharply tuned to one of the gas reradiating frequencies that we have selected." It further states that echoes are not received from either methane or ethane since these are symmetrical molecules and produce no frequency translation on reflection, or reradiation. The paper implies that propane reradiates with

frequency translation and that it is the gas which is detected by the radar. The radar operator is said to switch back and forth from hard object frequencies to the propane frequency. (It is assumed that the "hard object frequencies" means that the receiver is tuned to the same frequency as that transmitted, and that the "propane frequency" is when the receiver is tuned to a different frequency from that transmitted.) When the receiver is "sharply tuned to one of the gas reradiating frequencies that we have selected ... the hard targets are severely depressed, and only that radiation emanating from the desired petroleum gas molecules is displayed on the radar." This is a very definite description of the use of a frequency offset and is hard to contradict, but it is different from what is described in this report. The authors of ref 8 might indeed operate with a frequency offset as they describe. Nevertheless, the use of a frequency offset on receive can be questioned. The proponents of this concept need to satisfy those who are skeptical by providing more details of the method of operation (such as the frequency transmitted and the precise frequencies which are received).

The Chemistry Division of the Naval Research Laboratory was asked by the Defense Advanced Research Projects Agency (DARPA) to determine whether the postulated frequency-translation mechanism was a valid concept.⁹ They were not successful in identifying a theoretical basis that would predict a frequency translation of incident microwave radiation, nor could they find experimental evidence for a frequency translation. In work on this subject also supported by DARPA, Richard Copeland reported that no evidence was found for an interaction of microwave signals with various gases and mixtures when observed in a 300 ft length of waveguide acting as a test cell under laboratory conditions.⁶

In his 1984 final report (reference 6), Copeland shows scope photography of an oil field with the effects expected if hydrocarbon gas were present. He does not say whether the radar receiver is on frequency. In fact, he seems to imply it was off frequency. However, the nature of the scope photos, the stated frequency of the radar local oscillator, the filter bandwidth, and the center frequency and spectral width of the transmitted signal, make it likely the receiver was operated on frequency or very close to on frequency.

If there is a frequency offset, it should be expected that the energy at the offset frequency will be relatively weak. Most microwave devices that are designed specifically for the purpose of translating one frequency to another, usually do so with a significant reduction of energy. As a guess, 20 dB might be an optimistic value for the conversion loss. Therefore, it would be expected that a reradiated signal at a different frequency might be much weaker than the backscattered signal. If a signal were detected off frequency, an even larger signal might be found on frequency.

It is valid to ask what is happening when someone states they are detecting radar echoes from hydrocarbon gas with the receiver tuned to a different frequency from that which is transmitted when no valid theoretical basis has been found for a frequency translation, when a frequency translation has not been seen in the laboratory, when there are no details given about the specifics of the radar and echo signal parameters (such as the frequency or frequencies of the echo signals and their amplitudes), and the

absence of scope photography which shows echoes from gases but not clutter (clutter should not appear with a frequency offset). As described in Appendix A, when the above was discussed with Robert Owen he came to the conclusion he was operating with the receiver tuned to the same frequency as the transmitter. Based on this exchange of ideas with Robert Owen, as well as what has been reported here, it has to be concluded that the others who use this technique are very likely operating in the same manner with their receivers tuned on frequency, or nearly so.

If there are operators who actually detune the receiver, the following speculation is offered as a possible explanation of what might be taking place. (There is no way of knowing at this time whether or not this explanation is true, it is simply offered as a place to start.) If the radar is operated with high receiver gain, the display will be bright with unwanted clutter echoes that might mask any echoes from the gases. To see echoes other than clutter, the gain has to be lowered. The radar normally incorporates STC (Sensitivity Time Control) for this purpose when it is operated in its usual manner for detection of maritime targets--the application for which it was designed. The STC is not used when looking for gaseous echoes. It is turned off. The receiver gain can be reduced so that most of the clutter echoes are not visible, but echoes from the gases are still seen. (It will be recalled that the gaseous echoes were seen at a gain setting of 4 or 5, but not with a gain setting of 2 or 3.) If a high gain setting is used, the clutter will dominate. Instead of reducing the gain of the receiver, as was done in our observations, a similar result can be achieved by slightly detuning the receiver. Therefore, if someone detunes the receiver, it is suspected that the frequency offset actually used is not too far removed from the transmitter (not the tens of megahertz indicated in the patents), and that the receiver gain is relatively high and not at the levels used in the tests reported here.

It might be noted that a similar reduction in overall gain can be had by tilting the antenna beam in elevation so that the target is illuminated with less energy. This would not be easy to do with the radar antennas that have been used since their beamwidths have been typically about 20°; but it would be possible with an antenna of a few degrees beamwidth. However, turning down the gain is easier and serves the same purpose as raising the antenna or slightly detuning the receiver.

One of the keys to the success of Robert Owen was his recognition that the radar display could not be operated in a normal manner. A good radar operator will usually adjust the gain until the noise background just appears on the display, as evident by a slight whitening of the display. This occurred on the radar in our tests at a gain setting of about 7 or 8. We normally operated, however, at a gain setting of 4 or 5 in order to detect the desired echoes. If we operated at gain setting 7 or 8, where a radar of this type normally should, we would not have been as successful in detecting the desired echoes. If the receiver were detuned slightly, it would have been equivalent to operating at a lower gain setting.

The above may or may not be a valid explanation for the claimed operation of a radar with a frequency offset. It is a relatively simple matter, however, to determine how the radar actually operates when it is said to be tuned off frequency. The mystery of a frequency offset should

be resolved by observing in the field the method by which the radar is operated when it is supposed to be tuned to a different frequency from that transmitted. Unless proven otherwise, it is concluded that these radars are operated on frequency, and not as described in the patents and in the literature.

One of the reasons this method has probably not had the acceptance it should with the oil companies and others is that independent scientists can not accept the theory offered for its explanation. This is unfortunate since the theory probably is not correct. An incorrect theory should not cast doubt on results, and the results in the field appear to indicate a successful method for finding hydrocarbon gases using radar.

6. NATURE OF RADAR ECHOES FROM ATMOSPHERIC GASES

If the incident radar energy does not excite a reradiated signal at a different frequency, what other scattering mechanism might be able to explain the observed results? Scattering from the individual gas molecules is not a valid explanation since the backscatter is far too weak to be detected by radar. Based on previous radar exploration of scattering from the atmosphere, it can be said that radar echoes are obtained only from rain and other hydrometers, particulate matter (birds, insects or dust), turbulent variations of the refractive index (or dielectric constant) of the atmospheric gases, or from regions of ionization. There have been no other valid mechanisms identified. If someone wishes to explain why echoes are received from the atmosphere they must either apply one of the target models mentioned above or else offer new circumstances to make some other model valid. The most likely mechanism for explaining the cause of the radar echo is the atmospheric turbulence induced by the seeping gases. Radar energy is reflected from atmospheric turbulence. No other scattering mechanism has been able to account for the radar observation of distributed echoes from the clear atmosphere. It would be natural to postulate that the echoes observed by radar that are attributed to reflections from hydrocarbon gases are due to the turbulence of the atmosphere caused in some manner by the escaping gases. This model would normally be the first to be tested against the experimental observations, since it has worked well to explain other radar observations such as the reflection from convective cells and natural clear air turbulence.

The nature of radar scattering from the atmosphere has been investigated in the past in order to explain radar "angel" echoes (echoes not obviously associated with aircraft or other conventional radar targets) as well as radar echoes from meteorological effects.¹⁰ Radar echoes from the clear air can be explained as scattering from inhomogeneities in refractive index due to turbulence. The radar scattering from distributed volumetric scattering is described by the radar cross section per unit volume illuminated by the radar. It is usually designated η and is equal to σ/V , where σ is the radar cross section measured by the radar and V is the volume illuminated by the radar. The volume reflectivity η , according to Tatarski¹¹ is

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \quad (1)$$

where C_n^2 is the so-called structure constant which is a measure of the mean-square fluctuations of the refractive index, and λ is the radar wavelength. (This expression is based on the assumption of homogeneous turbulence which, although it may have doubtful validity in some circumstances, has been widely accepted for explaining the experimental results of atmospheric scatter.) In the normal atmosphere, at low heights, typical values of C_n^2 might range from 10^{-8} to $10^{-11} \text{ m}^{-2/3}$.¹² If radar reflections from hydrocarbon gases are to be explained by the turbulence model, C_n^2 will have to be greater than found in the normal atmosphere without the presence of hydrocarbon gases. The structure constant is defined as

$$C_n^2 = \frac{\overline{(n-n')^2}}{r^{2/3}} \quad (2)$$

where n is the (fluctuating) refractive index at point x and n' is that at point $x + r$. It is assumed that C_n^2 is independent of x and depends only on the separation r .

A simple calculation based on Eq 1, to estimate the order of magnitude of C_n^2 at X band, assuming the scattering region is 20 m in diameter and 20 m in height, gives C_n^2 approximately $10^{-6} \text{ m}^{-2/3}$ when the radar cross section is 0.01 m^2 . This is about two orders of magnitude greater than the reported measurements of C_n^2 for natural clear air turbulence at low altitudes.

This report does not attempt to develop a theoretical model based on turbulence induced in the atmosphere by hydrocarbon gases. It requires a larger effort than can be applied at this time. It is pointed out that atmospheric turbulence theory has been highly successful in explaining other electromagnetic propagation phenomena in the atmosphere and should be applied to the radar detection of hydrocarbon gases. However, to apply it, or any other model, to explain what the radar sees requires much better understanding of what is actually taking place physically. More needs to be done. For example:

- Are the concentration and structure constant of hydrocarbons sufficient to explain the radar observations?
- Can water vapor, which is known to be a major contributor to the microwave reflection from clear-air turbulence, be a factor?
- Could the presence of gas seepage increase the likelihood of enhanced natural convection which is then detected by the radar rather than detect the hydrocarbons themselves?

7. MISCELLANEOUS

This section includes other comments about the subject of the radar detection of hydrocarbon gases, some of which originated from discussions with Robert Owen.

Signal Processing. Currently, the decision as to the presence or absence of echoes from hydrocarbon gases is made with a rather conventional radar and by an observer viewing a conventional display. Modern signal processing methods might offer some potential for improved operation. Time compression, amplitude fluctuation measurement, and/or spectral analysis are possible things to consider. Signal processing should make the detection and recognition of hydrocarbon gases quicker and more reliable.

Viewing the PPI display on a single scan of the radar antenna has not been sufficient for recognizing the presence of hydrocarbon gases when using the present procedures. On a single observation, the "blobs" on the display that are from hydrocarbon gases appear similar to other clutter echoes. Target recognition is obtained from observing the distinctive fluctuations of the blobs from scan to scan (as well as the physical arrangement and extent of the blobs). A signal processing technique with potential for enhancing the recognition of a fluctuating signal is time compression. This device stores in memory a number of consecutive scans (7 to 10 might be typical when searching for aircraft echoes). The stored scans are played back speeded up. Fluctuating or moving target echoes are more readily distinguished from normal stationary clutter in the speeded up display. Thus the characteristic fluctuations from hydrocarbon gases might be more detectable with a time compression display than with a conventional radar display. Time compression offers the possibility of speeding up the decision, making the decision more reliable, and making it easier for an inexperienced observer to detect the desired effects that are characteristic of hydrocarbon gases as seen by radar.

Once a region of the PPI display evidences echoes that might be the result of hydrocarbon gases, further verification can be obtained by stopping the antenna to view one or more of the blobs as a function of time. This can be done by observing on an A-scope which displays the echo signal amplitude vs range. An A-scope not only provides the radial profile of the target echo (assuming the echo is of greater radial extent than the range resolution of the radar), but it also permits the fluctuation characteristics of the echo to be observed continuously. It is suspected that on an A-scope the fluctuations of the echo from hydrocarbon gases will be different from the echoes from other clutter. This can allow more reliable recognition of hydrocarbon gas echoes than by viewing only the PPI. A more quantitative approach to target recognition would be to obtain the spectrum (or the autocorrelation function) of those echoes suspected to be from hydrocarbon gases.

A B-scope might prove useful in better observing the echo rather than a PPI. A B-scope is a display in rectangular coordinates (as opposed to be polar coordinates of the PPI) of range vs angle. The B-scope spreads out the near-in region of the display more than does a polar display, so it might be easier to recognize the patterns of echoes when they are at close range.

Helicopter Mounting of the Radar. Robert Owen also operated his radar mounted on the front of a helicopter so that he can explore regions not accessible by road. He said he flies at a relatively low altitude (about 12 feet) so that the antenna is at about the same height as that on the van. The radar used in the helicopter is the same as that used in the van,

except the antenna is mounted upside down on a boom in front of the helo. The low altitude at which the helicopter flies implies that the scatterers are probably close to the ground, perhaps within several tens of feet. However, with a 20° elevation beamwidth, the "field of view" in height at a range of 1000 ft is about 330 ft. This means that when operating the helicopter radar at a height of 12 ft, the antenna will view targets which can be more than 150 ft above the ground when at a range of 1000 ft. Thus it is not clear why the helicopter has to fly so low.

There is, however, another reason the helicopter radar might fly low. The higher it flies the more clutter that will be seen. Clutter echoes are generally stronger than gaseous echoes and will make difficult the detection of the desired targets. By flying low, the natural contour of the ground can prevent the radar from seeing surface echoes so that gaseous echoes above the surface will not have to compete with clutter. This explanation is consistent with the observation made by Robert Owen that the helicopter should not be flown up hill (since more clutter is visible).

The vertical extent of the echo region can be determined by scanning a pencil-beam antenna in elevation. If gaseous echoes are evident from well above the surface, a narrow pencil beam which sees the gases but not the surface echoes will permit a helicopter to fly higher.

Improved Radars. The Raytheon Type 2700 marine radar is a very simple, inexpensive radar that has proven well suited for the detection of hydrocarbon gases. As far as is known, it is the radar which has been used by most (if not all) of the various organizations which use this radar technique to search for hydrocarbon gases. There are better radars that could be used. However, Robert Owen has stated that when "better" radars were used, the results were poorer. The reason for this is not clear (nor was it explored with Owen what was actually meant by the radar being better or the results being poorer). If better radars were indeed poorer, the explanation as to why they did not perform as well might offer an interesting clue as to the nature of the echo produced by hydrocarbon gases.

Although it is not understood what was meant by the above statement made by Owen, one reason why better radars might not appear to perform as well as the Type 2700 may be related to the sensitivity of better radars. A radar with increased sensitivity will see much more clutter than the Type 2700. Clutter can mask desired echoes when viewed on the conventional PPI. This will make difficult the detection and recognition of the echoes from hydrocarbon gases. As mentioned previously in this report, even with the Type 2700 the echoes from clutter can mask the gaseous echoes when the radar receiver is operated with full gain. Owen turns down the gain in order to detect the desired echoes in the presence of clutter. With a "better" radar capable of detecting weaker targets than the Type 2700, care would need to be exercised to insure that the desired echoes are not being masked by clutter. A more sensitive radar is not undesired. The gain can be reduced, and it might be better to operate with normal gain and look for targets at longer range. (A possible disadvantage of trying to detect this effect at longer range is if it lies within no more than a few tens of feet from the surface. If this is the case, detectability might be limited by masking imposed by the contour of the ground.)

Atmospheric Pressure. Robert Owen mentioned that he thought the effect is more readily detected when the atmospheric pressure is low.

Patent of L.W. Blau, et al. Robert Owen made the writer aware of the 1939 patent of L.W. Blau, which bears on the subject. The patent is based on the use of radio waves (or light) to detect hydrocarbon gas seepage associated with oil deposits. (Blau also states that the method can be used for the exploration of coal.) His method is what would today be called a forward scatter (or bistatic) CW radar. (A bistatic radar is one with the transmitter and receiver separated by a considerable distance. A forward scatter radar is a bistatic radar in which the transmitter, target, and receiver all lie on the same line. A monostatic radar is the conventional radar with receiver and transmitter at the same location, and usually with a single shared antenna for transmit and receive.) The radio transmitter and receiver are separated by several miles in one forward-scatter embodiment of Blau's patent, and the spectrum of the received signal is measured. The spectrum analyzer covers the absorption bands of the hydrocarbon gases. It is the selective absorption of the radio energy by the hydrocarbon gases which is said to be detected.

It is not known how successful this method was, or even if it was tried. This technique might be difficult to use since the amount of absorption introduced by the hydrocarbon gases is likely to be small relative to the variations in the path loss that might normally occur in propagating between the two antennas. The bistatic radar technique, with separations of several miles, make it difficult to localize the gases since it is not known where on the line connecting transmitter and receiver the echo might originate. The echo can be localized (by triangulation) by moving the transmitter and receiver to new locations. This can be complicated, however.

Whether or not the technique described by Blau is actually capable of working, it should be possible to detect the presence of hydrocarbon gases with forward scatter radar if the turbulent model mentioned previously in this report is correct; that is, radar detection of hydrocarbon gases is due to the atmospheric turbulence induced by the gases. The backscattered echo from turbulent atmospheric gases is normally small. Either a powerful radar must be used to detect turbulence or, if a small radar is used as it is here, the range must be short. A turbulent medium, however, has the unique property that its scattering cross section increases significantly with bistatic scattering angle. In the direction of forward scatter (the geometry described in Blau's patent) the echo might be many orders of magnitude greater than in the backscatter direction. Thus the forward scatter signal from atmospheric gases might be quite large. Furthermore, clutter targets do not have the same scattering characteristic with scattering angle as does a turbulent atmosphere. Therefore, the bistatic or forward scatter radar might have enhanced target-to-clutter ratio as compared to a conventional (monostatic) radar.

It is difficult to utilize the forward scatter signal by itself because it does not easily provide the target location. However, it might be useful as a surveillance sensor that finds the general area of the hydrocarbon gases and which then instructs the conventional (monostatic) radar to observe in those directions to recognize and localize the hydrocarbon gases. Thus the bistatic (or forward scatter) radar, with its greater sensitivity to

turbulence, might be used to find the regions where the conventional radar should explore. The higher the scattering region is above the surface, the more successful this might be, since the unwanted scattering from the surface can be reduced.

Hydrocarbon Gases and the Presence of Oil. The writer does not claim to be knowledgeable in oil and gas exploration, and has to accept what others say about the utility of hydrocarbon gas seepage as a means for locating the presence of oil and gas deposits. There appears to be some controversy as to the utility of gas seepage as an exploration tool. Hydrocarbon gas seepage has been credited for some large oil discoveries in the past, but the emergence of more sophisticated techniques by the exploration geophysicist has eclipsed the search for oil and gas by above-ground detection of gas seeps. Apparently, gas seeps are hard to recognize by conventional (non radar) detection methods since "most light hydrocarbons evaporate into the atmosphere and are quickly dissipated by air circulation."¹⁴ This behavior of hydrocarbon gases need not be unfavorable for radar. The radar might be a better detector than more conventional gas detection methods since the radar observes the integrated effect of the turbulence triggered by the gas over an "area" rather than make a measurement of a "point," as is the case with most other instruments.

Robert Owen pointed out to the writer the shimmering in the sunlight that can be visually seen in some places when the viewing angle of the sunlight is favorable. Shimmering, however, can also be due to heating of the ground. It should be straightforward to determine if the areas seen visually by the shimmering effect correlate with areas noted by the radar. Another, possibly related, phenomenon mentioned in the literature is that satellite photographs of oil fields sometimes show hazy anomalies on the images, for which there does not appear to be agreement as the cause.¹⁵ A possible explanation for the haze is distortion caused by gas seepage.

8. WHAT MIGHT BE DONE FURTHER

The following are among the things that might be done to better understand this phenomenon:

- Quantitative measurements should be made of the radar cross section of the echo and its variation with time, so as to verify the nature of the echo. If the echo is from a turbulent atmosphere caused by the presence of escaping hydrocarbon gases the magnitude of the radar cross section will not be large and should be smaller than most clutter. Predictions should be made based on the theory of radar backscatter from turbulent gases as to the magnitude expected of the radar cross section.
- Quantitative observation of the spatial and temporal characteristics of the echo should be made and correlated with any visual objects in the vicinity. Measurements should be made of the atmosphere's dynamic behavior and constituents (especially hydrocarbons and water vapor) in those regions indicated by the radar echoes as showing evidence of hydrocarbon gases. These observations should be made under controlled conditions in known gas and oil fields. Similar

observations need to be made in fields for which it is known that no oil or gas is present.

- In order of preference, the radar should be equipped with an A-scope, a pencil-beam antenna trainable in elevation, a spectrum analyzer, and perhaps a B-scope in order to better diagnose the nature of the target causing the radar echo. Time compression should also prove useful.
- It would be nice to determine whether there is a frequency dependence to this phenomenon. If it is atmospheric turbulence, the frequency dependence should be weak. (If there were actually a frequency shift on reradiation from the gas, the frequency dependence should be striking.) Radars at different frequencies would be needed to determine the effect of frequency. This can be expensive. Although it would be nice to do, it would seem better to do some of the other things mentioned before incurring the expense of radars at other frequencies, unless these radars were already available.
- If the echoes are due to reflections from turbulent gases in the atmosphere, they should be affected by the atmospheric environment. Wind should be expected to have an affect on the radar echo.
- The radar has been operated at relatively short range. It should be determined whether it is possible to detect this phenomenon at longer ranges with a more sensitive system.
- For the record, one should document quantitatively what is seen by the radar when the receiver is tuned off frequency as described in prior patents and other publications, and compare to what is seen when the radar is tuned on frequency.
- It is important to involve in this work persons knowledgeable in the physics of gas seeps and persons knowledgeable in convection and turbulence in the lower atmosphere so as to extend and quantify the atmospheric turbulence model proposed in this report as an explanation for what the radar is seeing.
- Calculation, based on turbulent scattering, should be made of the radar cross section expected from seeping gases, and compared with measurement. An estimate of the gas concentration and dynamic behavior should be made and checked by actual measurement in the field.
- It should be determined why this effect has not been seen over plowed fields or with heavy vegetation and trees.
- When a satisfactory theoretical model is devised, it should be verified by testing.

The Raytheon Type 2700 marine radar has proven quite adequate for exploring this phenomenon and except for the added instrumentation mentioned above, a better radar might not be absolutely necessary for further

understanding of what is taking place. However, the radar can be improved considerably. It would be good to do so if the means allowed it. Some of the things that might be done to the radar include:

- Use a higher power transmitter. Some marine radars have 3 or 4 times the power of the Type 2700. There are military radars, some available on the surplus market, with several hundred times the power. Higher transmitter power will allow detection at longer range, provided the range is not limited by terrain masking.
- A similar increase in range can be obtained by utilizing a low-noise receiver. A receiver with a transistor front-end might have a noise figure of about 2 dB as compared to the 10 dB noise figure of the Type 2700 radar.
- A large, pencil-beam antenna will improve the detection range and the resolution, as well as the ability to probe in both azimuth and elevation. In the above it was mentioned that a small pencil-beam antenna; such as was used in Texas in September, should be employed. This type of antenna might be about 3 ft in diameter. The large antenna mentioned here should be from 6 to 8 ft in diameter. Such an antenna could have a beamwidth of about 1°. It will define the vertical extent of the phenomenon and can determine whether detectable gases are present above the trees. At present, the radar is not used in regions where there are trees, probably because the wide elevation beamwidth of the Type 2700 radar results in echoes from the trees which mask the weaker desired echo. A 1° beamwidth should also better define the horizontal extent of the target than the current antenna with its 3° beamwidth.
- A slower antenna scan will increase the sensitivity of detection, but might make it more difficult to recognize the characteristic fluctuations associated with this target. It might be better to increase the scan speed so that the fluctuations from scan to scan can be better determined. The decrease in sensitivity with increasing scan speed might not be important because there is already adequate sensitivity (when operating at short range) and the shorter revisit time might provide some improvement due to scan-to-scan correlation.
- Suitable recording equipment should be used, especially tape recording of the radar output. This is far better than the recording of the radar display with the Sony since little is lost when directly recording the signal and playing back on a radar display.
- Marine radars also are available at S band. It might not be the most important thing to do, but the availability of such radars might make it interesting to try.
- In addition to radar, the laser in the forward scatter mode might have some potential for detecting the atmospheric perturbations that might be associated with this phenomenon. This is related (somewhat loosely) to the technique described in Blau's patent. It might also be of interest to operate a laser radar in the backscatter

mode.¹⁶ If absorption at resonant frequencies occurs and is strong (which has not been established), infrared sensing at the absorption and non-absorption frequencies might recognize the gas seepage.

9. CONCLUSIONS

The following summarizes the major conclusions that can be derived from this rather incomplete investigation:

- Radar has demonstrated it can detect an effect that is apparently associated with oil and gas deposits.
- It has been established that the receiver is tuned to the same frequency as that transmitted, which is unlike the description of radar operation given in the prior patents.
- The effect detected by the radar is postulated to be due to atmospheric turbulence caused in some manner by hydrocarbon gas seeping into the atmosphere.
- Further experiments to probe the true nature of the phenomenon using the type of instrumentation described in this report should be conducted. Such experiments can establish the nature of the phenomenon and provide a basis for a theoretical understanding as well as indicate better methods of using this phenomenon for the exploration of oil and gas.
- Now that the original explanation attributed to this phenomenon has been shown to be inoperative, the theorists need to reexamine what the radar is revealing so as to evolve a better theoretical understanding.
- A better understanding needs to be had of gas seepage and its effect on the atmosphere and its detection by radar.

The full potential of radar for the detection of oil and gas deposits does not seem to be realized as yet. This report indicates how to begin to understand the phenomenon that has been observed by radar.

Appendix A

MEETING WITH ROBERT OWEN ON FEBRUARY 27, 1987

The writer spent the morning of February 27, 1987 talking with Robert Owen, President of Hydrocarbon Gas Surveys, about his radar method for detecting hydrocarbon gases. My prior knowledge of his method of operation was limited, and what I knew was not completely consistent. I first became involved with this radar method after the NRL Chemistry Division, under DARPA sponsorship, had been investigating potential mechanisms for explaining the frequency translation, the supposed basis for this technique. DARPA was originally approached by Richard Copeland of Energy Data Systems, Inc., about funding for further exploring the technique. Dr. Copeland apparently became interested because of his knowledge of Robert Owen's use of radar.

Several radar experiments were conducted by Dr. Copeland under DARPA sponsorship. Neither the field measurements nor the laboratory work verified the method of operation described in the patents.

The writer became interested in the phenomenon because of the unusual method of detection; i.e., the frequency translation of the echo signal. A similar explanation was offered in the past to explain the results of an entirely unrelated phenomenon. It was concluded in that similar case that the reception of signals at a frequency other than that transmitted was due to the transmissions of other signals in the vicinity that were scattered by the target rather than be due to some physical phenomenon of the scattering object involving a frequency change. It was desired to determine whether a similar explanation was possible for the radar detection of hydrocarbons as practiced by Owen. (It did not, but there is a relation between the two in the turbulent nature of the gaseous scattering medium.)

Owen was asked several questions about the technique described in his patent that had troubled the writer. The figure in the patent shows the antenna looking at the ground. He was asked if it wouldn't be better to have the beam parallel to the ground. He said that he always operated with the beam parallel to the ground and did not look at the ground as indicated in the patent.

I asked how he determined how far to offset the receive frequency; noting that his patent gave as an example the receive frequency at 9361 MHz when the transmitter was at 9375 MHz. He said he did not know how far off the receiver was from the transmitter, that he had no way of measuring it. He said he simply tuned the receiver for maximum sensitivity. He was asked if he saw hard targets, such as clutter, as well as the desired hydrocarbon echoes, and was the clutter stronger than the hydrocarbon echoes. He answered yes to both questions. Then I said that he is probably operating on frequency rather than receiving at a different frequency from the transmitter. He agreed that this was probably so. This was very satisfying since it indicated the trouble with the theoretical model that could not be verified was not a basic problem. It could be ignored, and concentration placed on what the radar was actually seeing rather than on what the patents said the radar should be seeing. (Too often, experimental observations

are thrown out along with the inapplicable theoretical model that was proposed to explain the observations. A discredited theory should not discredit the experimental results.)

Owen then explained how he obtained the idea for microwave fluorescence as a means for finding oil. He knew that if an area was illuminated with strong ultraviolet light at night, seeps that indicate the presence of oil would produce fluorescence and be visible. When he learned that this could result in blinding anyone within view, he abandoned the use of UV and translated the concept to microwaves which would not cause blindness. Although there is no microwave fluorescence as there is at UV, Owen was fortunate and did find that radar could locate hydrocarbon gas seeps even though it was not based on his original concept for the physics. (There is an old engineering adage that "if it works, use it.")

Owen said he had conducted a 24 hour test, with a measurement every hour, and found the effect to persist. Also, he thought rain on the ground did not have a long-term effect.

He said he was not in business with Richard Copeland (a former DARPA contractor) and that he was not asked to help with the design of Copeland's experiments. He was called in, however, when they were in trouble.

Owen also said he got started by looking with various surplus radars that covered a wide range of frequencies, but that he liked X band best.

I noted to Robert Owen that the Gournay patent was very similar to his own and that it was unusual to have two such similar patents. He said that the Gournay patent was an infringement and that he was compensated for this by Gournay.

I was impressed that Owen had something that was real when he offered to drive me with his radar to a site about 45 minutes away to see for myself the effect on his radar. Unfortunately, I did not have time to do so, but that is why I returned in June to spend parts of two days riding in his van with the radar.

My impression was that Owen probably had a valid technique for observing hydrocarbon gases associated with oil or gas deposits, but that there has been confusion because the model he proposed to explain the effect could not be supported by theory or experiment. Although the model may be incorrect, Owen has apparently found a different phenomenon that provides a detectable radar echo.

Appendix B

RADAR CHARACTERISTICS AND ESTIMATE OF THEORETICAL PERFORMANCE

Raytheon Type 2700 Marine Radar

Frequency:	9410 +/- 45 MHz
Peak Power:	5 kW (magnetron)
Average Power:	0.6 W (0.00012 duty cycle)
Pulse Width (short range):	0.08 μ s
Pulse Repetition Frequency:	1500 Hz
Antenna Width:	35 in.
Polarization:	horizontal
Azimuth Beamwidth:	3°
Vertical Beamwidth:	20°
Gain (estimated):	330, or 25 dB
Rotation Rate:	23 rpm (2.61 s scan time)
Receiver Bandwidth:	10 MHz
Noise Figure:	10 dB

Number of hits received per scan: $n = \theta_B f_p / 6(\text{rpm})$

$$= \frac{3 \times 1500}{6 \times 23} = 32.6 \text{ hits} \quad (\text{B1})$$

n_e = effective number of hits integrated (includes integration loss): 18

Range calculation

$$R_{\max} = \left[\frac{P G^2 \lambda^2 \sigma n}{t e (4\pi)^3 k T_0 B F_n (S/L)_1 L_s} \right]^{1/4} \quad (\text{B2})$$

Solve for minimum detectable radar cross section σ_{\min} at a range of 1000 m (3280 ft), with system loss $L_s = 10$, signal to-noise ratio = 15 dB, and $\lambda = 3.19$ cm.

$$\begin{aligned} \sigma_{\min} &= \frac{(1000)^4 \times 2 \times 10^3 \times 4 \times 10^{-21} \times 10^7 \times 10 \times 31.6 \times 10}{5 \times 10^3 \times (330)^2 \times 10.16 \times 10^{-4} \times 18} \\ &= 2.5 \times 10^{-2} \text{ m}^2 \end{aligned} \quad (\text{B3})$$

$$\text{at } 500 \text{ m (1640 ft)}, \sigma_{\min} = 1.6 \times 10^{-3} \text{ m}^2 \quad (\text{B4})$$

$$\text{at } 300 \text{ m (980 ft)}, \sigma_{\min} = 2 \times 10^{-4} \text{ m}^2 \quad (\text{B5})$$

United States Patent

Owen et al.

1151 3,651,395

1451 Mar. 21, 1972

[54] **METHOD FOR EXPLORING THE SURFACE OF THE EARTH WITH ELECTROMAGNETIC ENERGY INCLUDING COMPARING RERADIATION CHARACTERISTICS OF GASES TO LOCATE ESCAPING HYDROCARBON GASES AT THE SURFACE EMITTED BY DEPOSITS OF PETROLEUM AND/OR NATURAL GAS AT DEPTH**

[72] Inventors: Robert L. Owen, New York, N.Y.; Julian M. Busby, Muskogee, Okla.

[73] Assignee: Advanced Geophysics, Inc., New York, N.Y. by said Owen

[22] Filed: Sept. 12, 1969

[21] Appl. No.: 857,488

[52] U.S. Cl. 324/6

[51] Int. Cl. G01v 3/12

[58] Field of Search 324/6, 58.5

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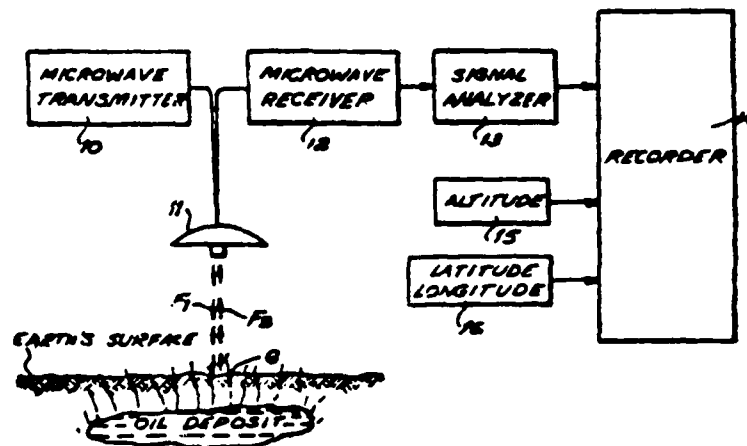
Primary Examiner—Gerard R. Stracher
Attorney—Mandeville and Schweitzer

[57]

ABSTRACT

The present invention makes use of the discovery of the fact that producing or potentially producing oil and/or gas fields usually have associated therewith at the earth's surface, the presence of escaping or permeating gases which have risen from underground stratigraphic and structural traps from which oil and/or natural gases may be recovered through drilled wells. Detection of the permeating gases is accomplished by focusing a beam of microwave radiation of known predetermined parameters thereupon, from remote locations, and measuring the parameters of the returned "reflected" microwave signals i.e., signals which are re-radiated by the hydrocarbons at the surface. Comparison of the frequency shift, and other parameters of the returned signal with the parameters of the transmitted microwave signal and correlation of the modified parameters of the returned wave with predetermined "microwave re-radiation characteristics" (MRC) of known gases will enable an immediate qualitative identification of a detected gas to be made and will enable an approximation of the quantitative concentrations of the detected gas to be made. Furthermore, by employing conventional navigational and cartographic procedures in association with the gas detecting practices of the present invention, it is possible to use ground vehicles and aircraft to explore, to prospect for, and to map gas and/or oil producing fields.

6 Claims, 2 Drawing Figures



United States Patent [19]

Gourney et al.

[11] 4,132,943

[45] Jan. 2, 1979

[54] REMOTE SENSING OF HYDROCARBON
GAS SEEPS UTILIZING MICROWAVE
ENERGY

[75] Inventors: Luke S. Gourney, Rockwall; John W.
Harrell, Duncanville; Charles L.
Dennis, Dallas, all of Tex.

[73] Assignee: Mobile Oil Corporation, New York,
N.Y.

[21] Appl. No.: 788,394

[22] Filed: Apr. 18, 1977

[51] Int. Cl.² G01V 3/12

[52] U.S. Cl. 324/6; 324/58.5 B

[58] Field of Search 324/6, 58 R, 58 B, 58.5 B;
340/237 R, 258 B; 73/40

[56] References Cited

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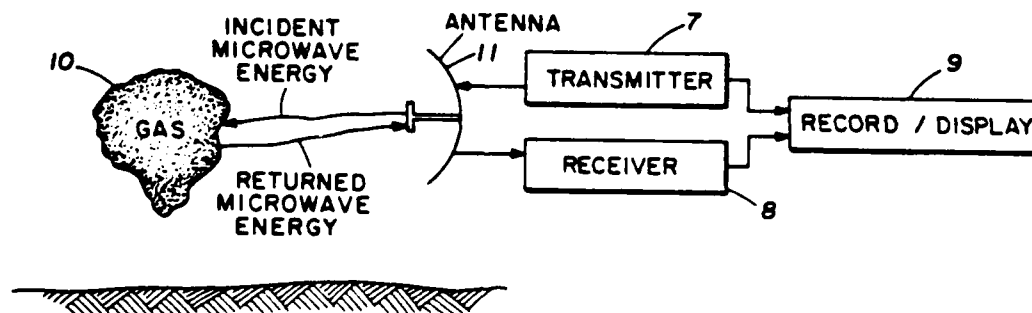
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Primary Examiner—Gerard R. Strecker
Attorney, Agent, or Firm—C. A. Huggett; George W.
Hager, Jr.

[57] ABSTRACT

A radar transmitter directs a beam of microwave energy at a first frequency through the atmosphere. A gas seep in the atmosphere irradiated by the beam of microwave energy is excited to emit microwave energy at a second frequency characteristic of the particular species of gas. A radar receiver is tuned to produce video signals representative of the microwave energy at the second frequency. An amplitude discriminator measures the amplitudes of the video signals during each radar sweep as an indication of gas concentration in the seeps and counts the number of video signals during each radar sweep as an indication of the size of the seeps.

10 Claims, 6 Drawing Figures



July 11, 1939.

L. W. BLAU ET AL

2,165,214

GEOPHYSICAL PROSPECTING WITH SHORT ELECTROMAGNETIC WAVES

Filed June 26, 1938

2 Sheets-Sheet 1

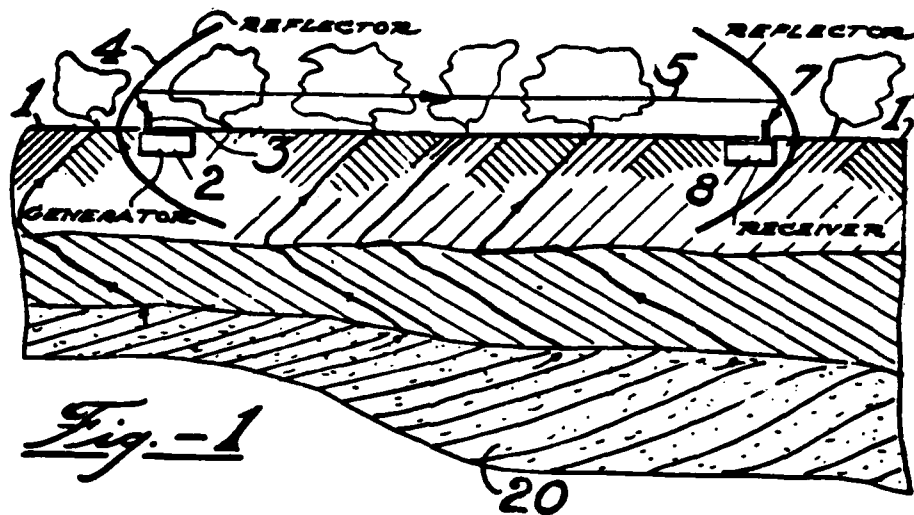


Fig. -1

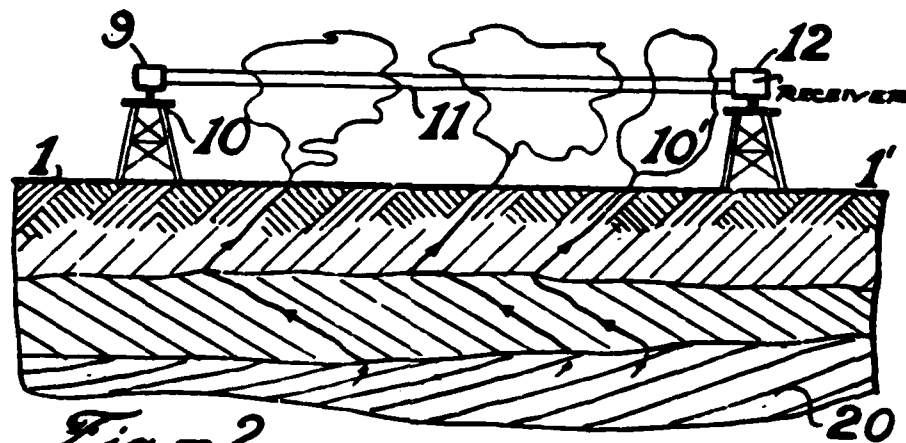


Fig. -2

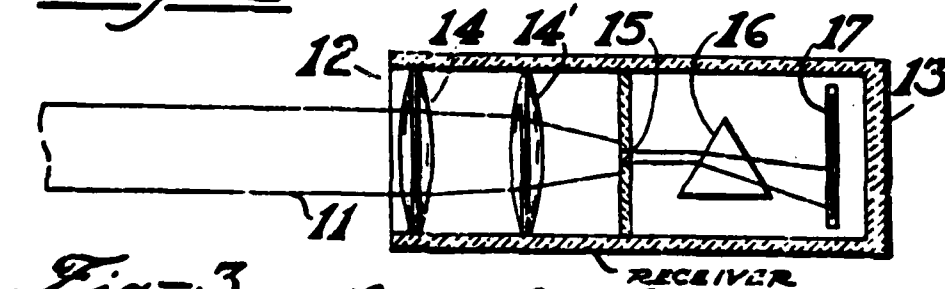


Fig. -3

Ludwig W. Blau
William B. Davis Inventors
By W. F. Weigster, Attorney

Appendix D

A-SCOPE DISPLAY

On the morning of September 17 during the tests near Decatur, Texas, an A-scope display was set up to examine the nature of the echoes that were received by the radar. The greater dynamic range of the A-scope display provides a different view of the echo properties than does the PPI display, examples of which were shown in Figs. 5 and 7 of the main body of this report. The Raytheon radar antenna was stopped in the direction of the suspected gaseous echoes as indicated by the PPI. Unfortunately, it was not possible to stop this particular antenna precisely at a given azimuth, so it is not completely certain that the desired targets were being examined on the A-scope. This is not a fundamental limitation, only a limitation with the particular instrumentation that was available for this test. It should be no problem to arrange a radar to observe the entire field of view and stop in a precise direction to examine a designated echo. All this is being said since it cannot be verified that what the radar observed on the A-scope was the suspected gaseous targets. It is for this reason that examples of the A-scope photos are included here as an appendix rather than incorporated in the main body of the report. Nevertheless, in spite of this caveat, the A-scope displays shown in Fig. D.1 are believed to contain echoes from gases as well as from natural clutter.

There are four photos of the A-scope display shown in Fig. D.1. In the upper right-hand corner of each photo is an insert of the PPI display showing the beam-pointing direction. (East is up, at 0 degrees.) The left half of each photo shows echoes from natural clutter. The general nature of this clutter is essentially the same in the four photos. In real time, these echoes appear to fluctuate rapidly as would be expected from natural clutter viewed by a X-band radar, but their average amplitude and location did not change with time. The two echoes in the middle of each photo, however, are believed to be from hydrocarbon gas seepage. They were of an entirely different character than the close-in ground clutter or hard targets (such as telephone poles, not shown here) that were viewed by the radar. These four pictures are included here to show how these echoes varied in amplitude and location as a function of time. Their "time constant" was not determined, but they seem to change in a time less than the rotation time of the radar (2.6 s). It is believed they changed their character within a second, but a precise estimate was not made. Although it cannot be said for sure that the distinctive echoes shown in the middle of each photo are caused by hydrocarbon gas seepage, they were at about the same range and angle as the gaseous echoes seen on the PPI, they fluctuated in time with the characteristics that resembled the gaseous echoes seen on the PPI, and they were unlike any other natural clutter usually seen by the radar.

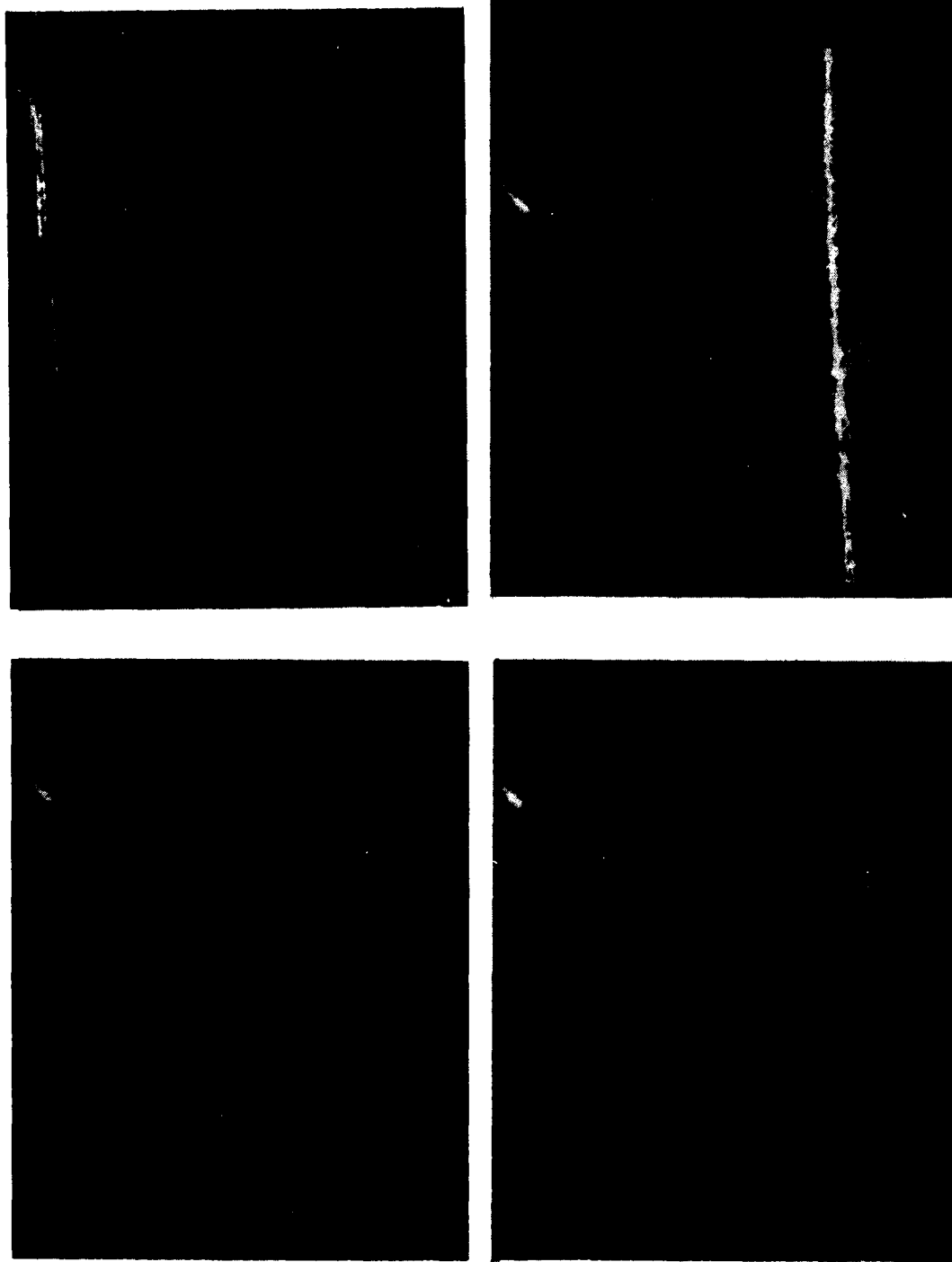


Figure D.1 - Four examples of the A-scope display with normal clutter echoes (at the left half of the trace) and two echoes (in the center of the trace) that might be due to reflections from hydrocarbon gas seepage. Note the variability in spacing and amplitude of these two echoes with time as compared to the relatively stable clutter echoes. The upper right hand corner of each photo is the PPI display showing the direction of the antenna beam.

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